A Drier Future?

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that is made by a cell-autonomous mechanism is usually influenced considerably by local environmental perturbations. Because the size change of somites observed in the mouse and zebrafish studies was not so drastic and was within the flexibility of a local autonomous mechanism, the existence of a local autonomous mechanism cannot be ruled out. If the size change was more extensive (greater than 200% or less than 50%), then the possibility of a local mechanism would be quite low.

The cooperation of the two different mechanisms offers many advantages. A local cell-autonomous mechanism can determine the size of a somite but cannot determine the absolute position of each somite. To form the regularly arranged array of somites, some global mechanism like the clock and wavefront mechanism is surely required. The clock and wavefront model does have some weak points, too. For example, it does not work for the most cranial four or five somites because they arise simultaneously (*8*). Another problem concerns the precision of the positional information given by the wavefront. Temporally, the concentration gradient of FGF is thought to act as the wavefront (in the chick, mouse, and zebrafish) (*5*). However, the slope of the gradient seems too gentle to indicate the precise timing to the oscillating cells. The model also cannot specify somite size along either the dorsoventral or the lateral axis. By incorporating a local autonomous mechanism to determine the somite size, these weaknesses are removed.

Although the cooperation of a global and local mechanism is possible, it leaves the most important question unresolved: What determines the size of somites? Dias *et al*. present a mathematical model mainly based on packing constraints of cells transitioning between a mesenchymal state and a polarized epithelium. But other processes transferring the long-range signal, such as diffusion, cell projection, and mechanical stress, could be mechanisms that determine the regular size.

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CLIMATE CHANGE

A Drier Future?

Global warming is likely to lead to overall drying of land surfaces.

Steven Sherwood[1] and Qiang Fu[2,3]

Global temperature increases affect the water cycle over land, but the nature of these changes remains difficult to predict. A key conceptual problem is to distinguish between droughts, which are transient regional extreme phenomena typically defined as departures from a local climatological norm that is presumed known, and the normal or background dryness itself. This background dryness depends on precipitation, but also on how fast water would evaporate. As the planet warms, global average rainfall increases, but so does evaporation. What is the likely net impact on average aridity?

Most studies of dryness focus on droughts rather than on the background aridity or changes thereto. They tend to rely on relatively simple measures that are useful for analyzing temporary anomalies but may not properly account for factors that govern the background state. Failure to explicitly account for changes in available energy, air humidity, and wind speed can cause some indices commonly used for identifying droughts to diagnose an artificial trend toward more drought in a warming climate (*1*). Recognition of this problem has undone past claims that drought is on the rise globally, and led to weaker claims about observed drought trends in the most recent Intergovernmental Panel on Climate Change report (*2*). However, that does not mean that conditions will not get drier (*3*, *4*).

Challenges in CLIMATE SCIENCE
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A different way of approaching the problem is to try to capture the changes in background state, rather than temporary anomalies such as droughts. This can, for example, be done using the ratio of precipitation (P) to potential evapotranspiration (PET) based on the Penman-Monteith equation (*1*, *5*). PET is the evaporative demand of the atmosphere, calculated as the amount of evaporation one would get, with given air properties, from a completely wet surface. Over a body of water PET equals the true evaporation, but on land, the true evaporation will be less than PET unless the soil is saturated with water. The P/PET ratio may be near zero in a desert but can exceed unity in wet climates. If the P/PET ratio falls, it means that conditions get drier; if it rises, conditions are getting wetter.

Recent observational studies have shown that P/PET is decreasing on average as the globe warms (*5*, *6*). Climate model simulations (see fig. S1, panel A) (*5*) predict that by 2100 under a high-emissions scenario, when climate is projected to be several degrees warmer than it is now, P/PET will drop much further in most tropical and mid-latitude land regions (see the figure). Such drops can shift a region to the next drier climate category among humid, subhumid, semiarid, arid, and hyperarid conditions (the latter four together are denoted dryland). In one simulation, the area of global dryland is projected to expand by ~10% by 2100 (*5*). Models predict that India and northern tropical Africa will become wetter, but nearly all other land regions are predicted to become drier. Under most scenarios, the drying would further intensify during the 22nd century.

Global averages of precipitation and evaporation must remain equal to each other on climate time scales. The observed and predicted drying tendency in P/PET over land thus implies that PET there increases faster than does global evaporation (noting that precipitation changes similarly on land and oceans). If there were no land on Earth, PET globally could not increase faster than P; they would always be equal. Thus, the increase in P/PET must be peculiar to land surfaces. One might expect complex land-surface

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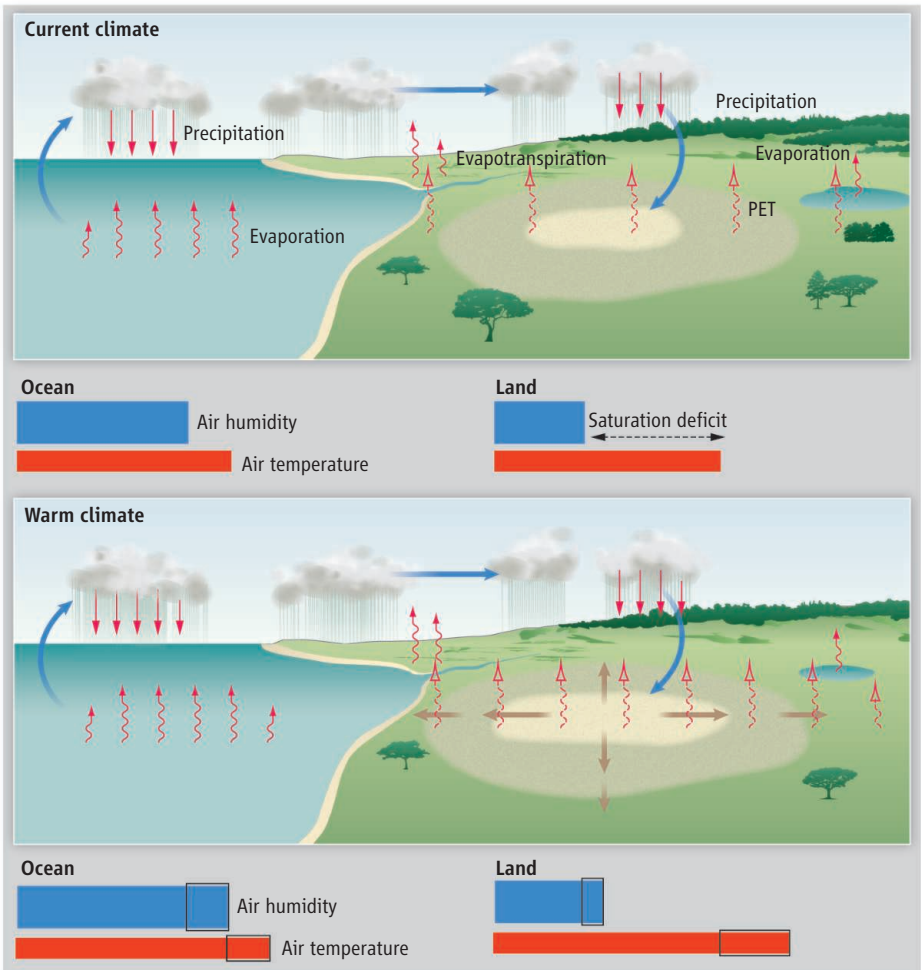

Warmer, drier. Aridity increases in warmer climates, leading to expansion of dry climate zones. Evaporation and precipitation increase modestly, but on land, evaporative demand (broken wavy arrows) increases faster than precipitation, because the strong increases in air temperature and consequently saturated water vapor concentration over land (red bars at lower right) exceed growth in actual water vapor concentration (blue bars). Increases in sensible and latent heat (associated, respectively, with temperature and water vapor, and represented by the area of each bar) have the same sum over land and ocean, with sensible heat increasing more over land than oceans and latent heat increasing more over oceans. Relative humidity (ratio of blue to red bar length) decreases over land.

responses involving soils or vegetation to be responsible, but recent research (*7*–*12*) suggests that the overall drying trend on land is rooted in relatively simple atmospheric thermodynamics.

The key factor causing drying is that land surfaces (and the air just above them) warm, on average, about 50% more than ocean surfaces (*7*). There is a simple and plausible explanation for this long-remarked phenomenon, at least for low and mid-latitudes. The atmosphere keeps convective instability (which gives rise to cumulus clouds) small over both land and ocean regions. This instability depends on the total latent and sensible heat in air near the surface. Because the latent heat (determined by atmospheric water vapor concentration) is smaller over land and changes less upon warming (see the figure), sensible heat (determined by air temperature) must change more, explaining the enhanced land warming (*7*, *8*). Indeed, if this enhanced warming did not happen, air over land would become less able to sustain clouds and precipitation, thus drying and warming the land via increased sunshine. Enhanced warming of land surfaces relative to oceans thus occurs simply because continental air masses are drier than maritime ones, which in turn is a consequence of the limited availability of surface water.

The second factor ensuring drying is that water vapor content over land does not increase fast enough relative to the rapid warming there. Nearly all water vapor in the atmosphere comes from the oceans, where the water vapor content of the overlying air increases by ~6% per degree Celsius of ocean surface temperature (*9*, *10*). When this air moves onto land, its typical water vapor content (though reduced) reflects the amount that it held originally (*11*). Because the land warms faster than the oceans, however, the humidity of the arriving air does not increase enough to maintain a constant relative humidity. The latter must therefore fall on average (see the figure), as indeed seen in model simulations (*11*, *12*) and observed on all continents (*10*). Therefore, the saturation deficit (gap between actual and saturation water vapor concentration; see the figure), which is the key factor controlling PET, grows much faster in percentage terms than do other hydrological quantities. This increases the aridity.

A map of the predicted change in annual mean near-surface relative humidity (see fig. S1, panel B) (*13*) not only confirms a general decrease over most land regions, but also shows a pattern nearly identical to that of the change in P/PET. These similarities show that regional changes in near-surface humidity, soil moisture, and precipitation are tightly coupled. Increases in PET are mainly attributable to overall land warming rather than relative humidity change (*14*), but the P/PET ratio on land is reduced largely by the enhanced land warming relative to oceans (see the figure) and by the decreases in relative humidity on land. The latter are negative over most land areas despite being slightly positive over oceans. Positive feedback from soil moisture changes is not needed to explain enhanced land warming, but likely amplifies it in some regions (*15*).

Regional variations in simulated aridity change may still be unreliable, or may reflect other changes such as poleward shifts of climate zones (*5*). But the general trend toward a drier land surface appears to rest on relatively firm foundations. The predicted drying would be sufficient to shift large portions of the Earth to new, drier climate categories (although the richer atmospheric CO_2 might mitigate the impact on some plants). The background drying is separate from, but may be compounded by, the expected trend toward more intermittent rainfall for a given mean rain rate (*16*).

As the above considerations show, focusing on changes in precipitation, as typical in high-profile climate reports (*2*), does not tell the whole story—or perhaps even the main story—of hydrological change. In particular, it obscures the fact that in a warmer climate, more rain is needed. Many regions will get more rain, but it appears that few will get enough to keep pace with the growing evaporative demand.

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Supplementary Materials

www.sciencemag.org/content/343/6172/737/suppl/DC1
Fig. S1
References

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CHEMISTRY

Capturing Surface Processes

A modified surface x-ray diffraction geometry allows dynamic restructuring of surfaces to be studied.

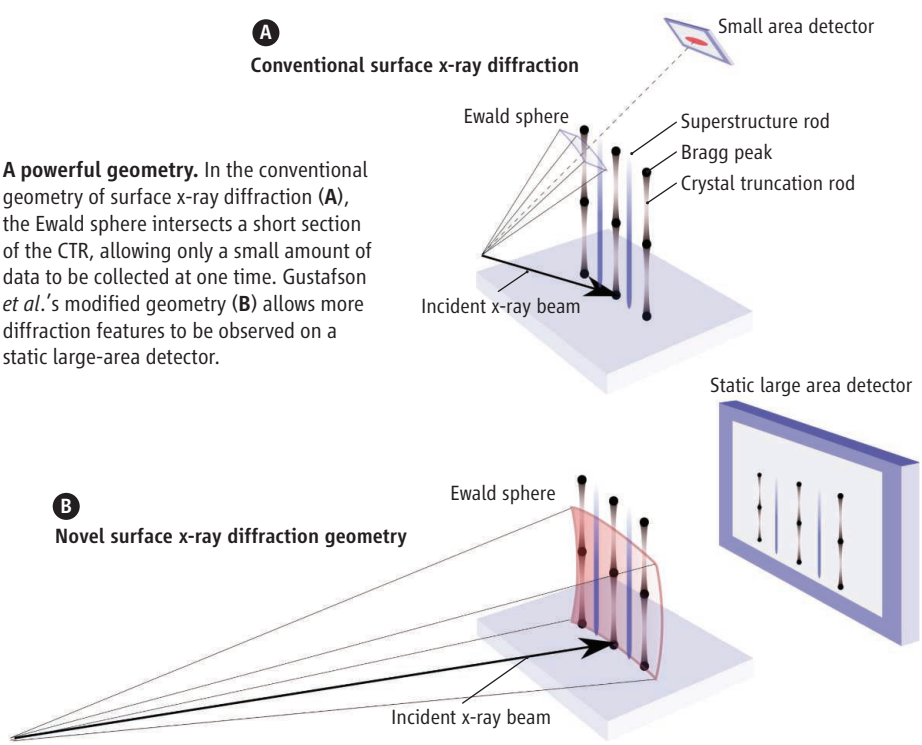
Chris Nicklin

The outer atomic layers of a solid or liquid play a central role in determining the properties of the sample as a whole, because it is here where the material interacts with the external environment. Detailed knowledge of the arrangement of atoms at a surface or interface between two materials is required to understand and tune the material's properties. This outer-layer structure is crucial for technological processes such as catalysis, lubrication, and electron transport. In surface x-ray diffraction, surface structures are investigated by directing high-energy x-rays at a sample at grazing angles of typically less than 1° (*1*). On page 758 of this issue, Gustafson *et al.* outline a different geometry for these measurements, using even higher-energy x-rays and shallower angles to allow faster data collection, enabling dynamic surface restructuring processes to be captured (*2*).

In surface x-ray diffraction, the diffracted intensity results from a combination of x-rays scattered from the bulk of the sample and x-rays scattered from its surface (see the figure). Intense Bragg peaks occur where the bulk scattering exhibits constructive interference. The truncation of the sample at the surface leads to streaking between the Bragg peaks in the direction perpendicular to the surface. These streaks, known as crystal truncation rods (CTRs) (*3*) show modulations in intensity that results from interference between the bulk-scattered and surface scattered x-rays. Additionally, ordered reconstructions of the outer atomic layers result in superstructure rods, which have an intensity profile that depends only on the surface scattering. Modeling these modulations can reveal the surface structure and registry with the bulk with a resolution of <0.05 Å. The ordered array of diffraction features (CTRs, superstructure rods, and Bragg peaks) formed by a single-crystal sample is known as the reciprocal space lattice.

Traditionally, surface x-ray diffraction measurements have required a high resolution diffractometer, which allows the sample and detector to be accurately positioned at specific angles relative to each other. These instruments usually have five or six independent rotation axes that enable a particular diffraction feature to be detected while maintaining the fixed angle of incidence (*4*). In most state of the art experiments, the scattered x-rays are collected by a small two-dimensional detector (*5*), where the intensity of the spot or streak on the detector results in a single point on the rod.

One way to understand the x-ray scattering process is through the Ewald construc-



A powerful geometry. In the conventional geometry of surface x-ray diffraction (**A**), the Ewald sphere intersects a short section of the CTR, allowing only a small amount of data to be collected at one time. Gustafson *et al.*'s modified geometry (**B**) allows more diffraction features to be observed on a static large-area detector.

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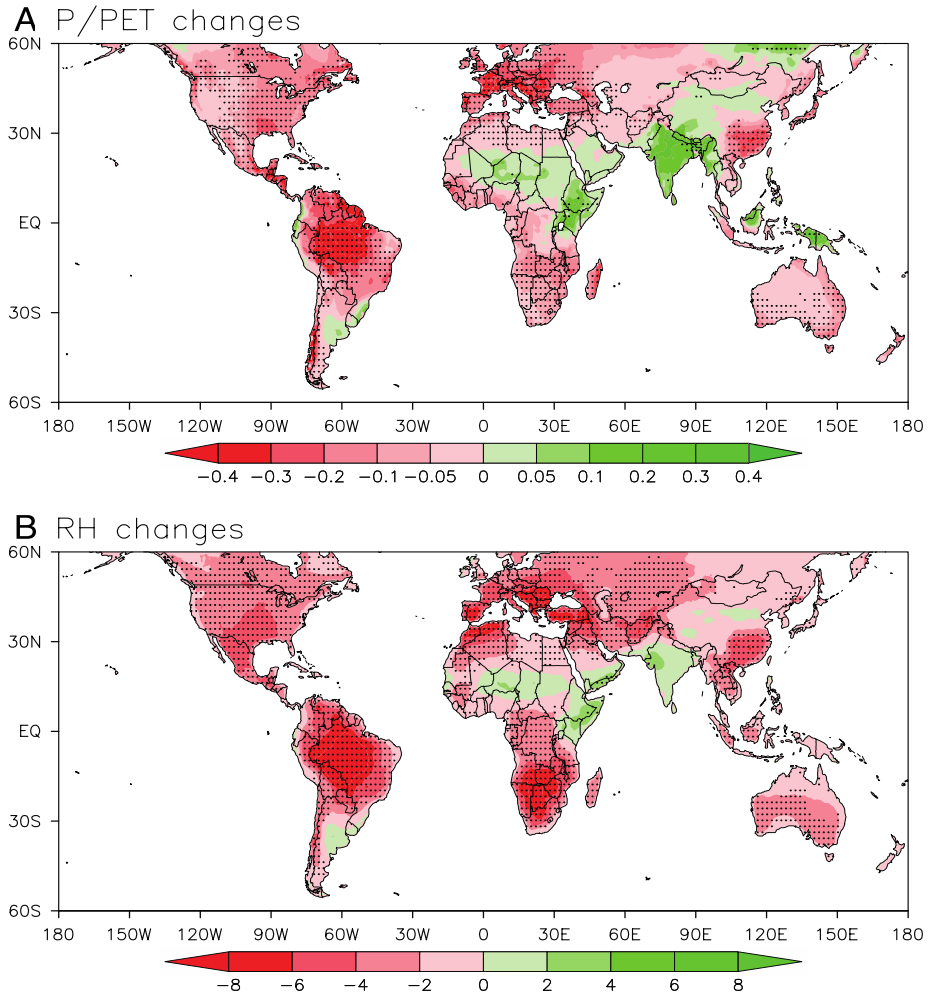

Fig. S1. Changes in aridity index [**A**, after (*1*)] and near-surface relative humidity (RH) [**B**, after (*2*)] simulated over land by 27 CMIP5 (Coupled Model Intercomparison Project v. 5) climate models by 2100 under a business-as-usual (RCP8.5) scenario. Simulations with detailed land hydrology models confirm that these changes imply increased water stress (*3,4*).

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